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Feeder bus network design problem: a new metaheuristic procedure and real size applications

F. Ciaffi*, E. Cipriani, M. Petrelli

Dipartimento di Scienze dell'Ingegneria Civile, Roma Tre University, Via Vito Volterra 62, 00142 Rome, Italy

Abstract

The present paper deals with the transit network design problem related to the feeder routes defined as transit services for the connection of local areas, where the demand has to be gathered, with the stops of the main transit network, usually railway or underground station. The objective of the research is the development of a procedure that simultaneously generates routes and frequencies of the feeder bus network in a real size large urban area.

The solving procedure is articulated in 2 phases: in the first one, a heuristic algorithm generates two different and complementary sets of feasible routes, in order to provide a good balance between maximization of the service coverage area and minimization of the overall travel time. First set is composed by circular routes, generated solving a travelling salesman problem (TSP) connecting the highest demand node pairs in the area with the stop of main transit network. The second feasible set aims at developing feeder routes more direct than the others using the k-shortest path algorithm. The set of all feasible routes, generated taking into account only the main skeleton of the road network, is then the input data for the second phase where a GA is utilized for finding a sub-optimal set of routes with the associated frequencies. The proposed procedure has been implemented on two real-life size networks, Winnipeg and Rome, in order to compare its effectiveness with the performances of the existing transit networks. The results of the applications of the design procedure show that the feeder routes imply a more integrated transit network with a reduction of the total travel time, despite an increase of the number of transfers, in a more efficient way as demonstrated by the reduction of the operating costs and the increase of the average load factor.

Keywords: Transit network design, Genetic algorithms, Feeder bus networks

* Corresponding author. Tel.: +39-6-57333339; fax: +39-6-57333486.
E-mail address: fciaffi@uniroma3.it

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1. Introduction

It is widely recognized that the remarkable increase in traffic congestion, air pollution, energy consumption and road accidents is produced by the large increase of individual car traffic. On the other side, shifting transport demand towards the public transport enhances urban sustainability making a better use of land, air and energy sources than individual transport mode. Based on such issues, this paper presents a methodology for solving the "Feeder Bus Network Design Problem" ("FBNDP") whose solution seems very useful to improve integration between main urban transit services, like rail and bus networks. FBNDP represents one of those new policies developed in last decade for managing and planning urban transit networks since it allows to design those specific bus lines suitable to cover residential areas, gathering transit demand and feeding main transit system in specific transfer points.

The structure of this paper is based on the procedure framework which represents the different steps of the work: firstly it is shown a wide review of other works about feeder bus networks design; next chapters, instead, deal with the problem formulation and its mathematical pattern and, most importantly, the solving procedure framework, based on two different phases. In the first one a heuristic procedure, solving a travelling salesman problem and a k-shortest path algorithm, generates two sets of feasible and complementary routes; in the second phase, instead, a genetic algorithm is proposed for finding a sub-optimal set of routes and associated frequencies. Finally is shown the application of the model to two different real-life size networks: the city of Winnipeg, in order to test the procedure quality, and the urban area of Rome, so as to compare its effectiveness with the performances of the existing transit networks.

Each one of these listed steps was completed taking into account all the typical FBNDP goals; the sub-optimal set of lines, routes and frequencies has been designed aiming at the balance between service coverage in the areas and service effectiveness and efficiency, and looking for the improvement of the integration between rail and bus networks in urban area of Rome.

2. State of the art

The transit network design is a complex non convex problem (Newell [1], Baaj and Mahmassani [2]). It is usually formulated as a non-linear optimization problem with both discrete and continuous variables and constraints. The best and most efficient solving methods are based on heuristic procedures but their applications are mainly limited to test cases or actual networks of small size. A global review about route design, frequency setting, timetabling of transit lines, and their combination is proposed by Desaulniers and Hickman [3], Guihaire and Hao [4], Kepaptsoglou and Karlaftis [5].

Over the last years, the evolution of operational research and computer technology has produced great and renewed attention for the transit network design problem; new approaches based on metaheuristic techniques (Genetic Algorithm –GA–, Simulated Annealing or Tabu Search) have been frequently applied to solve optimization problems. Due to the discrete nature of several variables of the transit network design problem as well as the nonlinearity and the non-convexity of its objective function, probabilistic optimization techniques such as GAs seem to be appropriate.

Despite this renewed attention for transit network design, still today there are few researches about feeder bus subject. Among the most remarkable there's the one of Chien and Yang [6], dealing with an alternative methodology for solving feeder bus route design problem in a typical urban irregularly shaped service area, based on a model for finding just the optimal bus route location and its operating headway. All this research starts from the assumption that demand is uniformly distributed within each zone of the service area but differs among zones and that it is no sensitive to service quality. An algorithm allows to design not the entire feeder bus network but a single bus service optimal route, based on a many-to-one travel pattern, aiming to the maximization of service coverage and demand gathering in the service area, having a line-haul distance of 10 km from the transfer station to be fed.

Differently from Chien and Yang research [6], the work proposed by Jerby and Ceder [7] aims not only to the definition of a methodology for a single feeder bus route design but to an entire feeder bus network planning. Their research is threefold: a) create a method for estimating potential demand for a shuttle bus service, b) elaborate a model focusing on optimal route automatic design and, finally, c) define a heuristic algorithm designed to take into account road networks of all sizes. All the work is based on a modular approach allowing the entire problem to be partitioned in a chain of sub-problems; first four stages are to estimate the potential demand, creating a base network of a defined service area using inputs and constraints like average travel speeds, maximum travel time and walking distances after the scan of urban entire network and the discard of all the links not used by transit service. Fifth and sixth steps show the model formulation proposed for this particular feeder route design problem, based on a decision variable aiming at maximizing potential demand and minimizing walking distances. Last two stages of the threefold research are about the heuristic algorithm framework, introduced to define circular routes in urban context, both starting and finishing in the same node with a total travel time lower than a fixed constraint.

Another research about FBNDP is the methodology, based on metaheuristic techniques, proposed by Shrivastava e O'Mahony [8], and its application to real life case of DART, the rapid transit system of Dublin. In this paper, most appealing innovation is represented by the application of a Genetic Algorithm (GA) in order to obtain the sub-optimal set of feeder bus lines and simultaneously the associated frequencies leading to a schedule coordination with main transit system (DART). Hence we can consider at the same time this solving procedure useful for both routing problems and scheduling problems.

Differently from this research, our paper adopts a design approach similar to the one proposed by Fusco et al. [9]. Specifically, methodology proposed in the present work is based on a route generation procedure specific for feeder bus network in order to design a basin of different and complementary lines; then, a genetic algorithm combines the candidate lines in order to find a sub-optimal network of feeder services.

3. Problem Formulation

The feeder bus network design is formulated as an optimization problem consisting in the minimization of all resources and costs related to the public transport system with fixed demand. The optimization problem can be formally defined as follows:

$$\left(\hat{\mathbf{r}}, \hat{\mathbf{f}}\right) = \arg\min \; z\left(\mathbf{r}, \mathbf{f}, \mathbf{q}_{\mathrm{t}}^{*}\right) \tag{1}$$

subject to hyperpath assignment on transit network and to a set of feasibility constraints that define both minimum and maximal values for route length and bus frequency, where the notations have been introduced are:

- z is the objective function;
- $\mathbf{r}$ is the vector of routes;
- $\hat{\mathbf{r}}$ is the vector of optimal routes;
- $\mathbf{f}$ is the vector of lines frequencies;
- $\hat{\mathbf{f}}$ is the vector of optimal frequencies;
- $\mathbf{q}_{\mathrm{t}}^{*}$ is the equilibrium vector of segment flows on the transit network;
- Λ is the user route choice model function;

- $\mathbf{C}_t$ is the vector of path generalized costs on the transit network.

The objective function z is defined as the sum of operator's costs z_1 and users' costs z_2 plus an additional penalty related to the level of unsatisfied demand z_3:

$$z(\mathbf{r},\mathbf{f},\mathbf{q}_t^*) = z_1(\mathbf{r},\mathbf{f}) + z_2(\mathbf{r},\mathbf{f},\mathbf{q}_t^*) + z_3(\mathbf{r},\mathbf{f},\mathbf{q}_t^*) \quad (2)$$

The transit users' costs are a weighted sum of in-vehicle travel time, access time, waiting time and a transfer penalty. Transit operator's costs are computed as a combination of total bus travel distance and total bus travel time. To provide transit services to as many transit users as possible, another additional component is included in the objective function z. This supplementary term represents a penalty that is proportional to the unsatisfied transit demand of the design network and reflects the need to reject the banal solution of minimum cost ("zero users and zero service"). Solutions characterized by large increase of the unsatisfied transit demand are also discarded. Thus objective function formulation, similar to the one proposed by Cipriani et al. [10] for main transit network design, is developed to properly weight "z_1", "z_2" and "z_3" terms, in order to represent specific needs of feeder bus networks.

The input data are the public transport demand matrix, the characteristics of the road network and the rapid rail transit system, the operating and users' unit costs. Outputs are bus routes and their frequency as well as the total costs and the vector of flows on the public transport network.

4. Solution approach

The proposed solution framework consists of two main stages:

1. a heuristic route generation algorithm (HRGA) that generates a large and rational set of feasible routes, by applying different design criteria and practical rules;
2. a genetic algorithm (GA) that finds the optimal network of routes and their frequencies.

Of course, given the well-known non-convexity of the problem and the heuristic nature of the method, there is no guarantee that the solution found, indicated as $[\hat{\mathbf{r}},\hat{\mathbf{f}}]$ in equation (1), will be optimal. In other words, the outcome of the heuristic procedure corresponds to a (known) minimum that is local with regard to the (unknown) global one.

In the first phase of the solution procedure (Stage 1), a heuristic algorithm generates two different and complementary sets of rational and realistic routes (K-shortest path and TSP type routes). This provides a large set of feasible routes that are nevertheless quite diversified among them, because they are built according to typical feeder bus network design criteria. Therefore balance between effectiveness and efficiency (user or operator point of view) and maximization of service coverage in the area and improvement of integration between rail and bus networks represents the principles which led us in choosing main elements of HRGA. The "K-shortest path" type routes are composed by many and direct short routes connecting main system stations (transfer points) with any centroids laying in our service area, in order to minimize total travel time for transit users and total operating costs for operators. The TSP-type routes come from the application of "Travelling Salesman Problem algorithm" and connect all centroids to railway or subway stations with a single path (the shortest); therefore, based on such issues, TSP-type routes are less than K-shortest ones since only few complementary paths fulfil the initial goal of maximization of service coverage and demand gathering in the area.

The resulting set of feasible routes is the basin from which the GA select routes to build a network (Stage 2). The design variables are transit routes and the GA is implemented in the MATLAB language while the fitness evaluation requires computing, for each solution generated, the three terms of the objective function by simulating the public transport network with the software EMME (INRO, 2007). As the performance of the transit system depends on the service frequencies, which should be optimized depending on the passenger volumes, an iterative assignment and frequency setting procedure, first introduced by Baaj and Mahmassani [11], is applied.

4.1 Heuristic route generation algorithm

The first component of the solution framework is the HRGA. Two complementary sets of candidate routes are generated by HRGA applying different design criteria and practical rules.

The HRGA is divided into the following five sequential steps:

- Step 1: Generation of the K-shortest type routes;
- Step 2: Generation of the TSP-type routes;
- Step 3: Storage of the K-shortest and TSP-type routes in the overall set of routes;
- Step 4: Check of the feasibility constraints (maximum and minimum allowable route length) for all routes stored in the basin;
- Step 5: Set feasible routes as input data for the GA.

The first set of feasible routes is called “K-shortest type”. The route generation criterion reflects the users' point of view and is addressed to develop direct lines seeking routes effectiveness; it is composed by the “k” shortest paths connecting the main transit network stations with any single centroid laying in the service area. The order “k” of the paths represents a positive integer chosen in order to increase line influence in covering more zones of study area. Solving procedure is implemented in Matlab and is based on Dijkstra algorithm, because of its capability of finding paths and trees of lowest cost with high computational speed in each kind of graph. Therefore two of the inputs required are source node and destination node and specifically, in our application, first one was each centroid in the area while second one was the railway station to be fed. Application of Dijkstra algorithm needs another important input as the total travel distance matrix among all the regular nodes of road network, built taking into account the length of every edges in the graph.

Last but not less important input for K-shortest-type routes is the parameter "k"; its value has to be chosen in order to design a wide range of "k" alternative and feasible routes between each centroid and the railway station to be fed. Therefore, in our application, this choice was made taking into account location of traffic zones and railway stations in our service area and road network features.

The second set of feasible routes is based on a completely different approach, which aims at reducing passengers' access impedance allowing a widespread demand gathering in service area. The design strategy, based on Travelling Salesman Problem Algorithm, seeks to provide service coverage in the area since also circular but rational routes are accepted even if they might increase total travel costs for both users and operators.

From the user's point of view, the obvious increase of in-vehicle time with respect to the K shortest-type routes should be balanced by some positive expected aspects, as lower access time to the network. From the operator's point of view, the network composed by this family of routes seems less efficient than that composed by all K shortest-type routes due to the deviousness of the lines but it allows a service coverage improvement in the service area, typical goal of feeder bus network design problem.

As it is well known "TSP" is a minimization problem of connecting all vertex of a graph with the lowest cost path, starting and finishing at a specified vertex after having visited each other vertex exactly once. In this work this family of routes derives from a TSP algorithm based on a Genetic Algorithm (GA). For this reason two inputs required for generation of TSP routes family with this solving procedure are number of iterations of GA and number of individuals of the population to be evaluated. Two other parameters have to be taken into account to apply TSP-algorithm: first one is the total distance matrix between all centroids of service area while the second one are the coordinates "X" and "Y" of any centroid; varying the number of GA iterations and the number of individuals of GA population is possible to obtain a wide range of alternative and feasible TSP routes, starting and finishing at the railway station to be fed after having visited each centroid of the service area exactly once. As it has been already described, generation of this kind of routes follows the main goal of providing the service coverage improvement in the area, the demand gathering maximization and, from users' point of view, the minimization of auxiliary access time to the transit network.

At the end of K-shortest type and TSP-type routes generation, all routes generated are checked to verify if feasibility route constraints are satisfied. In particular, the constraints concerning the maximum and minimum allowable route lengths are investigated. If the constraints are satisfied the routes are stored in the set of feasible routes as input data for the second phase of the solution framework.

4.2 Optimal bus network calculation

The second stage of the solution framework is characterized by the use of the genetic algorithm (GA) to find the optimal sub-set of routes and their frequencies. Genetic Algorithms are stochastic optimization algorithms founded on the applications of concepts of natural selection and natural genetics and have been used in recent years to solve many optimization problems. The transition scheme of GA simulates the natural evolution of a population and investigates the solution space by applying a probabilistic search process to all the individuals representing a population of solutions simultaneously. In general, the “best” individuals of any population of solutions tend to reproduce themselves and survive to the next generation, thus improving successive generations. GAs explore all regions of the solution space by applying genetic operators (mutation, crossover, selection and elitism) that simulate the reproduction of individuals in the population. Crossover takes a pair of individuals and generates two new individuals (their offspring) by combining their chromosomes’ sets. Mutation provides a probabilistic modification of the chromosomes that may alter the reproduction process. Elitism is used to save the few best individuals that tend to reproduce and survive to the next iteration, thus improving successive generations.

In our application (Section 5), resulting from the HRGA procedure are about 80 routes. The set containing these routes is the basin from which the GA picks to build up a network; for instead, in case of a population composed by 50 individuals, any composed by 10 chromosomes, any generation presents 50 networks, any composed by 10 lines, randomly picked from the basin containing the 81 lines. Any route is identified by a code (line number); any network is represented as a string (in this example, 10 characters long). For any individual (network) the objective function value is computed. Then, a linear fitness scaling is performed in order to convert the raw objective function scores to values ranging in an interval suitable for the roulette wheel selection that has been implemented in the present algorithm. Once two parents have been selected, the crossover operator randomly selects half of the chromosomes from the first parent and half from the second one, and combines the selected chromosomes to generate the offspring. Mutation operator replaces, with a mutation probability equal to 1.5%, each chromosome of the individual with a new chromosome (line) chosen randomly from the basin. Reproduction options that have been utilized to create the next generation are: elitism fraction equal to 10%; crossover fraction, other than elite fraction, equal to 85%; mutation fraction equal to 15%.

The GA has been implemented in the Matlab language too; the Emme scripting language is used to perform transit assignments required for the evaluation of the objective function. The fitness evaluation requires computing, for each solution generated, the three components of the objective function by simulating the public transport network. As the performance of the transit system depends on the service frequencies, which should be optimized depending on the passenger volumes, an iterative assignment and frequency setting procedure, first introduced by Baaj and Mahmassani [11], is applied. The procedure consists of an iterative process between the transit demand assignment and the route frequency setting equation:

$$f_i = \frac{q_{hk,i,\max}}{fc_{\max} \cdot C_V} \qquad (3)$$

where $q_{hk,i,max}$ is the maximum segment volume of line i as resulting from the assignment. The procedure stops when the maximum difference among route frequencies in two consecutive iterations is lower than a given threshold. The convergence of the iterative frequency setting procedure is not guaranteed, but all computational tests performed converged in few iterations.

5. Real size network application

The proposed procedure has been implemented on a medium-size actual network in order to compare its effectiveness with regard to the performance of the existing transit network. As explained in the introduction of this paper, before the application of our model on the Rome transit network, the methodology has been tested on the Winnipeg transit network in order to evaluate the sensibility of the solution search process to the weights adopted in the objective function and the best network configuration varying the number of bus lines. As it's widely shown in Cipriani et al. [12], this calibration has been carried out taking into account mainly the comparison between access time weight and transfers weight, since they have been considered the best parameters to represent the typical FBNDP goals: specifically auxiliary access time weight stands for maximization of service coverage aim while transfer weight represents the objective of improving integration between bus network and rail network. Then, three additional tests have been carried out on Winnipeg network in order to assess a suitable number of lines composing the sub-optimal feeder network. Specifically 10, 15 and 20 lines networks have been compared and on the base of such results, a feeder network made of 10 lines has been considered as the suitable for a study area of medium size like Winnipeg and Rome.

5.1 Rome real-life network application

A FBND methodology has been applied to two north-western suburbs of the city of Rome, Aurelio and Primavalle, located in the 18th and 19th districts; they represent the study area of about 20 km^2 and with a population of about 125,000 inhabitants. Existing main transit network is composed of two lines: one subway line, Metro A, and one urban railway service, FR-3 Roma-Cesano; transfer points chosen to be fed lay just on these two lines: Battistini, terminus of the Metro A line, and Gemelli, stop of FR-3 urban railway. The existing bus transit network is, instead, composed of 15 bus lines, with many overlapping routes and average lines headway of about 15 minutes. In order to offer a regular service in the study area, respecting planned headways on each line route, in the morning peak hour operator needs about 120 vehicles. Despite this huge number of required buses, average and maximum volumes don't exceed 35% and 76% respectively. Transit demand in the morning peak hour amounts to about 13,000 trips with almost 8000 users (the 60% of the total amount) exiting from the service area.

Once defined its geographical and network features, the study area has been divided in two basins, one for each railway station, on the base of the road network structure and the resulting access impedance; according to this partition into two different sub-areas, each railway station has been considered fed by only a part of all centroids, whose demand has been considered attracted by the basin reference station. The HRGA has allowed the identification of a set of feasible routes composed by 81 elements (66 K-shortest type routes and 15 TSP-type routes), which represents the basin for the application of GA for finding optimal solution. According to preliminary results, previously shown, individuals composed by 10 chromosomes (i.e. 10 lines bus network) have been adopted. Differently, a varying size of the population has been considered creating five scenarios, each composed by a different number of individuals (10, 20, 30, 40 and 50).

GA was run on a PC Pentium 4 with a 1.86 Ghz processor and 1 GB of RAM for a computation time of about 15 hours for 100 iterations. Such computation time depends on the number of iterations necessary to obtain a significant reduction of the objective function.

All scenarios gave the expected results but "Scenario 3", composed by 6 K-shortest type routes and 4 TSP-type and obtained with a GA population of 50 individuals, has been considered as the best network due to its balance between transfers increase and the decrease of all others OF components.

Specifically, Table 1 shows the performance comparisons between existing and best network, analyzing the values of the different terms of the objective function; this has been evaluated by assigning all transit demand on entire network and taking into account only the results of our study area; the rest of entire network has been considered invariant in time and space. In the last line, it's provided the comparison, in terms of percentage differences, among our best solution and the existing network of 15 bus lines in the study area.

Table 1. Performance comparison between existing and designed network of 10 lines (#)

Scenario	*Lines*	*OF Value*	*Transf.*	*In-veh time*	*Access time*	*Wait. time*	*Unsat. demand*
	(n)	*(n)*	*(n)*	*(min)*	*(min)*	*(min)*	*(n)*
Existing	15	183,545	16,520	305,591	166,530	73,172	1,582
Scenario 3	10	140,245	24,474	284,133	125,237	73,188	987
Δ(%)	*-33*	*-24*	*48*	*-7*	*-25*	*0*	*-38*

Actually the comparison between the existing network and the proposed one shows that larger amount of transit demand in the study area can be served more effectively (reduction of 25% of the access time and decrease of 38% of unsatisfied demand) by a bus fleet composed by a lower number of lines (reduction of 33%) in a more efficient way (reduction of 7% of in-vehicle time), while still guaranteeing the same waiting time as the current network. At the same time, boarding increase represents, instead, a natural consequence of a route design procedure based on the initial goal of improving integration between rail and bus network (one transfer per passenger is due to the boarding from bus to railway). The analysis of pedestrians volume distributions shows that the design network has allowed an improvement of service coverage in the study area. Analogously the passengers volume distribution highlights an increase of almost 3000 passengers on the FR-3 and of 800 passengers on the first links of Metro A. This consideration is confirmed by analyzing also the comparison between distribution of transit volumes on the entire railway network, showing an increase of users on entire route of FR-3 between our optimal scenario and current network.

Table 2 shows a summary of best design network characteristics; as it can be seen average headway, number of vehicles needed, average line length and average running time also decreased:

Table 2. Best network features compared with existing network ones.

	Number of vehicles (n)	*Average Headway (min)*	*Average length (km)*	*Average running time (min)*
Existing (A)	119	15,6	18	85
Scenario 3 (B)	60	11,4	9	36

Table 3. Classification of existing and design network in terms of headway

Network	*Number of lines* *(n)*	*Headway ≤ 4 min* *(% lines)*	*5 min < Headway ≤ 15 min* *(% lines)*	*15 min < Headway ≤ 30 min* *(% lines)*
Existing	15	0 (0%)	8 (53%)	7 (47%)
Scenario 3	10	3 (30%)	3 (30%)	4 (40%)

Detailed comparison between the existing and the "10 lines" designed network in terms of line frequency is reported in Table 3. It is possible to see above that feeder network is mostly composed by high frequency lines (headway equal to 4 min), differently from the existing network. At the end, in order to have a more homogeneous comparison between our optimal solution (Scenario 3) and the current network, we optimized the frequencies of the current network since, as exposed in chapter 4, our solving procedure optimizes all the frequencies of each line on the base of transit volumes. The comparison shows an increase of "current" operative costs (veh-h and veh-km), both equal to 3%, due to the maximization of service coverage and the increase of associated lines frequencies.

All these results represent the achievement of improving integration between bus and rail modes since passengers use mainly the rail network to complete their trips reaching their final destinations, after an initial stretch of route on optimal feeder network given by the model.

6. Conclusions and further developments

In this paper, authors propose a procedure for solving the feeder bus network design problem in a urban area characterized by a multimodal transit system. The solving procedure consists of a set of heuristics, which includes a first routine for route generation based on two different algorithms (TSP and K-shortest path), in order to achieve all the typical goals of feeder bus network like improving integration between rail and bus transit systems; in the second phase a genetic algorithm is implemented for finding an optimal or near-optimal network of routes with the associated frequencies. Main novelties introduced by this paper are the adoption of a new heuristic procedure for route generation process and the application of the transit network design methodology, suited for feeder bus networks, to an actual urban area (the city of Rome).

The application of various generation criteria in the HRGA has led to a consistent, diversified and exhaustive set of feasible routes. The implemented Genetic Algorithm has proved to be robust and effective in producing reasonable solutions. Numerical experiments carried out on network of the city of Rome highlighted that the study area can be served with a more extensive demand gathering in respect of our initial goals of maximization of service coverage (reduction of 25% of the access time and decrease of 38% of unsatisfied demand) by a bus fleet composed by a lower number of lines (reduction of 33%) in a more efficient way (reduction of 7% of in-vehicle time), while still guaranteeing the same waiting time as the current system.

Further developments will be focused on supplementary analysis for the definition of feasible routes generated only on the main skeleton of road network in order to reduce its complexity. Additional effort has to be spent in the specification of the objective function in terms of components and weights to improve the effectiveness of the procedure by the transportation point of view. Additional refinements and improvements of GA efficiency or the use of other metaheuristics techniques (like PSO) are necessary for the reduction of computational times.

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